Type III interferons suppress influenza A virus infection independently of STAT activation by triggering cell death

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Type III interferons (IFN-λ1–λ4) are known to limit influenza infections *in vivo* and are non-redundant to type I interferons (IFN-α and IFN-β). Here, we demonstrated *in vitro* that type III interferons secreted by infected epithelial cells limit infection with influenza A virus (IAV). This effect occurs independently of STAT1 and STAT2 activation. Knockout of the IFN-λ receptor subunit IFNLR1 results in a slight reduction of STAT1/2 phosphorylation during infection with IAV, but leads to a substantially increased fraction of IAV-infected cells and higher levels of viral RNA and protein in the cell population. In contrast, knockout of the IFN-β receptor subunit IFNAR1 results in a pronounced reduction of STAT1/2 phosphorylation but a smaller increase in IAV proliferation. We propose that type III interferons limit the spread of IAV by promoting death of IAV-infected cells and demonstrate that the ratio of dying to infected cells is lower in IFNLR1 KO cells compared to wild-type cells. Overall, our results suggest an additional non-transcriptional role of type III interferons in the control of viral infection.

Keywords: innate immunity / cell signaling / interferons / respiratory viruses / cell death

Key points:

- IFNAR1 deficiency leads to a significant reduction of STAT1/2 activation in cell populations infected with IAV and a small decrease in IAV proliferation.
- IFNLR1 deficiency leads to a small reduction of STAT1/2 activation in cell populations infected with IAV and a significant increase in IAV proliferation.
- IFN-λ controls the proliferation of IAV (but not RSV) independently of STAT1/2 signaling.
- IFN-λ signaling increases the ratio of the dead to the infected cells, likely promoting death in IAV-infected cells.

Introduction

The discovery of type III interferons significantly expanded our awareness of the complexity of anti-viral mechanisms in innate immunity (Kotenko *et al*, 2003; Sheppard *et al*, 2003). This novel cytokine family, consisting of interferons λ1, λ2, λ3, and λ4, was initially believed to be mostly supplementary or even redundant to a much better described and understood family of type I interferons (represented importantly by interferons α and β, but also including several others). This was due to similarities between both cytokine families in the mechanisms of their production, recognition, activation of signaling pathways and downstream expression of target genes. Their production is triggered by recognition of pathogen particles by the same cellular pathogen recognition receptors and is dependent on activation of transcription factors NF-κB and IRF3/7 (Osterlund *et al*, 2007). Type I and type III interferons bind to their cognate receptors, IFNAR1/2 and IFNLR1/IL10R2, respectively, to activate the JAK/STAT pathway, which mediates phosphorylation of STAT1 and STAT2 (collectively referred to as STAT1/2) (Mesev *et al*, 2019). These two transcription factors form a complex with IRF9 and initiate expression of the so-called interferon-stimulated genes (ISGs), which allow the cell to enter a state of increased viral resistance and help activate adaptive immune responses (Schoggins, 2019). These common characteristics of type I and III interferons are generally not shared by type II interferon, IFN-γ, which exhibits a distinct immunomodulatory mode of action and is secreted mostly by specialized immune cells (Schoenborn & Wilson, 2007).

Despite their similarities, accumulating *in vivo* evidence suggests that the roles of type I and III interferons in response to viral infections are partially divergent, with IFN-λ playing a significant role in containing influenza A virus (IAV) infections. In animal studies, Galani *et al*, 2017 demonstrated that IFN-λ suppresses the initial viral spread, ensuring optimal viral clearance, while, in the case of high-dose infections, type I interferons are activated later to enhance antiviral and pro-inflammatory responses. Accordingly, IFNLR1-deficient mice display enhanced type I IFN production, and lethality. Klinkhammer *et al*, 2018 showed that IFN-λ, not type I interferons, conferred long-lasting antiviral protection in the upper airways against influenza virus transmission. A more significant role of type III interferons compared to type I interferons was also observed in mouse models for other viruses, including rotavirus (Pott *et al*, 2011), norovirus (Nice *et al*, 2015).

The non-redundant and significant role of IFN-λ is puzzling. Despite single reports of type III interferons uniquely inducing certain genes in specific cell lines: *Mmp7*, *Serpinb1a*, and *Csprs* in mouse IEC cells by IFN-λ1 (Selvakumar *et al*, 2017); or *CXCL10, CXCL11, IFIT3, IFI30*, and *TDRD7* in HECV cells also by IFN-λ1 (Caine *et al*, 2019), transcriptome profiling

studies have established that the type I and type III signatures are overlapping, and the ISGs induced by type III IFNs are a subset of those induced by type I IFNs (Lazear *et al*, 2019 and references therein). The major difference is in kinetics and magnitude of expression of genes stimulated by type I and III interferons – strong and rapid in the first group, weaker but more sustained in the second group. In their review, Lazear *et al*, 2019 characterizes type I *versus* type III interferons as having respectively high/low potency, rapid/slower kinetics, inflammatory/less inflammatory, systemic/restricted by anatomic barriers. Observations indicate that the expression of IFNLR is generally limited to epithelial surfaces of the airways, gut, liver, urinary tract and the blood–brain barrier, being especially high in the airway epithelium, which contrasts with a much more ubiquitous expression of IFNAR (Lazear *et al*, 2015; Wack *et al*, 2015). Such localized expression of IFNLR predisposes type III interferons to play a major role in combating infections with respiratory viruses. Thus to some extent the distinct role of type III interferons observed in animal models can be attributed to differences in their expression and the expression of their cognate receptor.

In this study, we show that IFN-λ plays a distinct and significant role in limiting infection with IAV, but not with respiratory syncytial virus (RSV), in respiratory epithelial cells in vitro. As expected, we observed that prestimulation with IFN-β leads to higher accumulation of ISGs than prestimulation with IFN-λ1, resulting in a stronger inhibition of both IAV and RSV proliferation. Upon viral infection, activation of STAT1/2 is dramatically reduced in IFNAR1-deficient but not in IFNLR1-deficient cells, whereas, surprisingly, proliferation of IAV (but not of RSV) is better facilitated by the deficiency of IFNLR1 compared to the deficiency of IFNAR1. Since IFNLR1 has no ligands other than type III interferons (Peterson *et al*, 2019), this indicates that IFN-λ confers protection against IAV through mechanisms beyond JAK/STAT signaling. We observed that the ratio of infected to dead cells is higher in populations of IFNLR1-deficient cells compared to wild-type (WT) cells, indicating that IFN-λ may also play a role in promoting the death of infected cells, thereby limiting viral spread.

Results

Stimulation with IFN-β elicits stronger STAT1/2 response and higher ISG accumulation compared to stimulation with IFN-λ1

Type III interferons are relatively weak inducers of STAT signaling in A549 cells. As shown in Figs. 1A and 1B, stimulation with IFN-λ1 (at its saturation concentration of 50 ng/ml) results in lower levels of phosphorylated STAT1/2 (p-STAT1/2) after 1 h, after intermediate times (2 and 6 h), and after longer times (24 and 48 h) compared to stimulation with IFN-β (also at its saturation concentration of 1000 U/ml; saturation concentrations for IFN-λ1 and IFN-β were

determined in Fig. EV1; all replicates of Western blots used in this study are shown in supplementary Source Data S1). Consequently, stimulation with IFN-λ1 compared to IFN-β leads to a lower accumulation of STAT1, STAT2, and three important ISG-coded proteins: RIG-I, PKR, and OAS1 (Figs. 1A and 1B). Similarly, mRNA levels are significantly lower after stimulation with IFN-λ1 compared to IFN-β for 15 out of 16 analyzed ISGs important in the regulation of the innate immune response (Fig. 1C).

Prestimulation with IFN-β inhibits virus proliferation more markedly than prestimulation with IFN-λ1

In our previous study, we have demonstrated that a 24-hour prestimulation with IFN-β reduces IAV RNA count by approximately 300-fold and RSV RNA count by about 5–10-fold (Czerkies et al. 2022, Fig 2A and 2B therein). Consistent with the weaker activation of ISGs by IFN-λ1, we have found that a prestimulation with IFN-λ1 has a lesser effect; it reduces IAV RNA count by about 5–10-fold, while the reduction for RSV RNA is insignificant (Czerkies et al. 2022, Figs. 2A and 2B therein). The effect is similar at multiplicity of infection (MOI) of 0.1 and 1. The difference between IFN-β and IFN-λ1 is also evident in the number of cells infected with IAV: the prestimulation with IFN-β leads to an about 15-fold reduction in the infected cell count, whereas the prestimulation IFN-λ1 leads to an about 4-fold reduction (Czerkies et al. 2022, Fig. 4 therein).

Here, we confirm the more substantial effect of prestimulation with IFN-β compared to IFN-λ1 (for infections with either IAV or RSV) by Western blotting. In the case of an infection with IAV (Figs. 2A and 2B), a 24-hour prestimulation with IFN-β (compared to mock) leads to markedly higher levels of p-STAT1/2, and, consequently, to higher accumulation of STAT1/2 and ISGs observed at 24 and 48 h post infection (p.i.). This results in drastically lower IAV nucleoprotein (NP) levels, below the detection threshold for all combinations of the MOI and time p.i. The effect of IFN-λ1 prestimulation (compared to mock) is faint — p-STAT1/2 and ISG levels are only slightly elevated, and IAV NP levels are on average about 3-fold lower. In the case of an infection with RSV (Figs. 2C and 2D), p-STAT1/2 levels (at 24 and 48 h p.i.) are similar for non-prestimulated and IFN-λ1- or IFN-β-prestimulated cells, indicating that a sufficient amount of IFN-β is produced during infection to trigger STAT1/2 phosphorylation. However, the early accumulation of ISGs, observed in Figs. 1A and 1B after IFN-β prestimulation, resulted in about 10-fold reduction of RSV fusion (F) protein levels (compared to non-prestimulated cells), not observed in the case of IFN-λ1 prestimulation (Figs. 2C and 2D).

In summary, we have shown that (pre)stimulation with IFN-β, compared to IFN-λ1, leads to a higher level of p-STAT1/2, higher expression of ISGs, and, consequently, when applied before viral infection, more effectively reduces viral spread.

IFNLR1 knockout markedly promotes IAV spread while modestly influencing STAT1/2 activation

In previous experimental protocols, cells responded to a specific interferon provided in prestimulation and, at later stages of the infection, to type I and type III interferons secreted by infected cells. To disentangle the effect of a single type of interferon during viral infection we employed A549 knock-out cell lines: IFNAR1 KO, IFNLR1 KO, and IFNAR1 & IFNLR1 double KO (further referred to as DKO). We found that although IFNLR1 deficiency has a modest impact on p-STAT1/2 levels and ISG accumulation, it significantly increases IAV NP accumulation ($p < 0.001$; approximately 3-fold higher than in WT cells), indicating enhanced virus propagation (Figs. 3A and 3B). The small decrease in p-STAT1/2 levels in the IFNLR1 KO cell population can be explained by a higher fraction of IAV-infected cells, in which (as we demonstrated previously) p-STAT1/2 levels are reduced (Czerkies *et al*, 2022). In contrast, the lack of IFNAR1 results in a high reduction of p-STAT1/2 and STAT1/2 levels as well as ISG accumulation, but does not lead to a significant change in IAV NP levels. Furthermore, when comparing IFNAR1 KO and DKO cells, we observe that the additional loss of IFN-λ signaling leads to an increase in the IAV NP level (Figs. 3A and 3B).

This suggests that IFN-λ slows IAV propagation independently of STAT1/2 signaling. This effect is not observed in the case of infection with RSV, which exhibits a slightly lower accumulation of its F protein in IFNLR1 KO cells compared to WT cells. Given the substantial variability in viral protein levels between experimental replicates, Figs. 3B and 3D present the quantification of eight replicates for IAV and seven replicates for RSV (two from our earlier study, Czerkies *et al*, 2022, and the remaining performed for the current study). Full quantifications, including mock infections and 24 h p.i., can be found in Figs. EV2 and EV3. The increased spread of IAV in IFNLR1 KO cells, compared to WT cells, is also reflected at the IAV RNA level. Digital PCR measurements (Fig. EV4) indicate approximately 3-fold higher accumulation of IAV RNA (for MOI=0.01 and 0.1, 24 to 96 h p.i.), in good agreement with the Western blot results.

Finally, higher levels of IAV mRNA and NP protein observed in IFNLR1 KO cells (but not in IFNAR1 KO cells) with respect to WT cells correlate with a higher fraction of infected cells, shown in Fig. 4A and 4C. We thus showed that IFNLR1 deficiency increases IAV NP, IAV RNA, and the fraction of infected cells (with respect to WT), without substantially changing p-STAT1/2 levels and accumulation of ISG-encoded proteins.

Functions of IFN-λ extend beyond induction of ISGs

As shown in the previous section, during IAV infection, lack of IFNLR1 does not significantly hinder the production of the considered ISG-encoded proteins but leads to significantly higher levels of viral RNA, viral proteins, and a greater fraction of infected cells. To exclude the effect of ISG production resulting from IFNLR1 activation, we performed an immunostaining experiment comparing the fraction of IAV-positive cells in WT and IFNLR1 KO cell populations. We prestimulated the cells with 100 U/ml IFN-β for 24 hours before infection with IAV (MOI = 1) and lysed 24 h p.i. (Fig. 4B and 4D). We used a high MOI and a lower IFN-β concentration, because IFN-β prestimulation substantially inhibits IAV spread. We observed that the fraction of infected cells was about 6-fold higher in IFNLR1 KO cells compared to WT cells. This implies that IFN-λ signaling suppresses IAV spread even more effectively when expression of ISGs is already ensured by IFN-β prestimulation.

In summary, we demonstrated that IFN-λ signaling hinders viral spread during an infection with IAV (but not with RSV), and this effect is independent of its regulation of expression of ISGs. In the following sections, we argue that IFN-λ signaling is linked to cell death (without distinguishing between apoptosis, pyroptosis, or other cell death types), which is crucial for eliminating infected cells.

Measuring an increase in the cell death rate

We postulate that IAV-infected IFNLR1 KO cells are more resistant to cell death compared to WT cells, allowing for faster virus proliferation. The natural inclination is to compare the number of cell deaths in IFNLR1 KO and WT cell populations infected with IAV. However, a change in the cell death rate affects the total number of infected cells, rendering a direct comparison impossible. Instead, the ratio of cell death events to the number of infected cells is a much more reliable indicator of an increased cell death rate. We clarify this by adapting the susceptible, infected, removed (SIR) model (Eqs. 1–3) to represent viral infection of the cell population, interpreting the removed cells (*R*) as dead. The kinetics are given by the following equations:

$$S' = -\beta I S \qquad (1)$$

$$I' = \beta I S - \lambda I \qquad (2)$$

$$R' = \lambda I \qquad (3)$$

where $'$ denotes differentiation with respect to time, β denotes the infection rate, and λ denotes the death rate. In Fig. 5, we show time trajectories of observables *R*, *I*, and their ratios for varied values of parameters β and λ for an MOI of 0.1 (see Fig. EV5 for MOIs of

0.01 and 0.3). The fraction of dead cells R can increase with λ (at early times) or decrease with λ (at later times), and is generally not monotonic with respect to this parameter (Fig. 5A). This occurs because, at higher λ, the infection progresses more slowly, leading to an overall lower fraction of infected cells (Fig. 5B). However, since the fraction of infected cells (I) is also strongly affected by the infection rate β (Fig. 5C), it cannot be used alone to distinguish between a decrease in mortality and an increase in infectivity. In contrast, the ratio R / I changes strongly and monotonically with λ (Fig. 5D), but weakly and not monotonically with β (Fig. 5E).

In summary, a simultaneous increase in the virus-infected cell fraction (I) and a decrease in the ratio of dead to virus-infected cells (R / I) indicates a decrease in the death rate λ. An important detail is that when experimentally measuring the proportion of infected cells (by immunostaining) or viral proteins or RNA produced by infected cells (by digital PCR or Western blot), we account for live infected cells but also some already dead infected cells. Fortunately, the monotonicity of the ratio R / I with respect to λ implies monotonicity of the ratio $R/(I + \alpha R)$ for any $\alpha \geq 0$. Furthermore, even when $\alpha = 1$, the ratio $R/(I + R)$ still grows substantially with λ (Fig. 5F).

IFN-λ signaling suppresses viral spread by promoting cell death

In Fig. 6A we show that the ratio of cell deaths to accumulated IAV NP is higher in WT cells than in IFNLR1 KO cells, which is equivalent to showing that the ratio of dying to infected cells is higher in the case of WT than IFNLR1 KO cells. The left column of Fig. 6A presents results from Western blots and shows the ratio of IAV NP between IFNLR1 KO and WT cells at 24 h p.i. and 48 h p.i. The amount of IAV NP increases significantly ($p < 10^{-7}$) in IFNLR1 KO cells, consistent with previous experiments (compare with Fig. 3B), despite the high variability observed between experiments.The right column of Fig. 6A shows the ratio of the fraction of cell deaths (measured by FACS) between IFNLR1 KO and WT cells for the same experimental protocol. On average, the ratios are only slightly higher than 1, indicating that the fraction of dead cells in IFNLR1 KO cell populations is comparable to that in WT cell populations. Since the ratio of viral proteins is higher than the ratio of cell deaths, we may conclude that the overall death rate is higher in WT than in IFNLR1 KO cells ($p < 0.01$).

RSV provides a relevant comparison, as it is known that its NS1 protein effectively blocks cell death, promoting viral spread (Bitko *et al*, 2007). To compare cell death rates during infection with IAV and RSV, we measured fractions of cells displaying propidium iodide signal during 24 and 48 hour long infections. Next, the cells were fixed, and fractions of virus positive cells at 24 and 48 hours were measured based on immunostaining images. In Fig.

6B, we show that cell death fractions for RSV and IAV are similar, but the infected cell fraction is much higher for infection with RSV than for infection with IAV. Consequently, this indicates a higher death rate for IAV infections compared to RSV infections ($p < 0.01$). The effect is observed for both WT and IFNLR1 KO cells. This supports our reasoning that an inhibition of cell death can be manifested by an increase of the fraction of infected cells rather than a decrease in the fraction of dead cells, suggesting that IFN-λ signaling suppresses viral spread by promoting cell death.

Discussion

Using WT, IFNLR1 KO, IFNAR1 KO, and IFNLR1–IFNAR1 DKO A549 cells, we demonstrated divergent roles of type I and type III interferons in control of IAV and RSV proliferation. (1) We showed that (pre)stimulation with IFN-β leads to a strong increase of p-STAT1/2 and STAT1/2 levels, high accumulation of ISGs, and, through those mechanisms, a pronounced reduction of proliferation of IAV as well as RSV. Prestimulation with IFN-λ (compared to IFN-β) results in lower levels of p-STAT1/2 and STAT1/2, lower accumulation of ISGs, and only moderately reduces proliferation of IAV, and does not reduce proliferation of RSV. (2) Next, we showed that in IAV- or RSV-infected IFNAR1 KO cells, p-STAT1/2 levels are pronouncedly reduced (with respect to WT cells), while the effect of IFNLR1 knockout on p-STAT1/2 levels is weak. However, IAV proliferates significantly faster in IFNLR1 KO cells than in WT or IFNAR1 KO cells. This indicates that IFN-λ suppresses IAV proliferation independently to STAT signaling. We note the possibility that IFNLR1 inhibits IAV proliferation independently of type III interferons, however mouse studies indicate that type III interferon deficiency has the same consequences as IFNLR1 deficiency during infections with norovirus, reovirus, and influenza virus (Peterson *et al*, 2019). The faster viral propagation in IFNLR1 KO cells is not observed for RSV. (3) Finally, we showed that absence of IFN-λ signaling significantly increases the level of IAV protein and the fraction of infected cells, without an increase in the fraction of dead cells. With the help of a simple mathematical model we interpret this observation as the ability of IFN-λ to promote early death in cells infected with IAV. Additionally, we showed that for infection with IAV, the ratio of dead to infected cells is higher than for infection with RSV. This is in line with earlier observations that NS proteins of RSV very effectively suppress cell death in infected cells, promoting virus proliferation (Bitko *et al*, 2007). This could explain why the effect of IFN-λ on RSV spread appears negligible.

Although divergent roles of type I and type III interferons have been highlighted in numerous studies, reports of a non-transcriptional role, especially of a proapoptotic (or propyroptotic) role, of IFN-λ are scarce. In two studies not related to infections, it was shown

that in intestinal cells type III interferons (compared to type I interferons) are a more potent inducer of apoptosis (Li *et al*, 2008) and pyroptosis (preprint: Sposito *et al*, 2022). Major et al (Major *et al*, 2020) found that IFN signaling (especially IFN-λ) hampers lung repair by inducing p53 and inhibiting epithelial proliferation and differentiation, which potentially can also promote cell death. Broggi et al (Broggi *et al*, 2017), in a study not directly related to infections, showed that IFN-λ regulates functions of neutrophils (known to have high expression of IFNLR) independently of transcription, and that treatment with IFN-λ induced in these cells a reduction in the phosphorylation of AKT at Ser473 and Thr308, which could make these cells more prone to cell death. Earlier, Denisova et al (Denisova *et al*, 2014) showed that inhibiting AKT suppresses proliferation of IAV in A549 cells. In the context of viral infections, a straightforward demonstration that IFN-λ increases the cell death rate is challenging because a higher cell death rate does not necessarily result in a greater fraction of dead cells, as it also suppresses viral propagation. We suspect that this may partially explain why this phenomenon was not reported earlier.

Our findings confirm that the role of IFN-β is to promote an antiviral state in not yet infected bystander cells, which increases their resistance to infection and/or slows down virus replication once they are infected. In terms of the SIR model, the effect of IFN-β can be seen as a reduction of the infection rate coefficient β (see Eq. 2). The role of IFN-λ (apart from STAT signaling) would be to promote cell death, and thus removal of infected cells. In the SIR model, this corresponds to an increase of the death rate coefficient λ (see also Eq. 2). In this picture, type III interferons are more universal than type I interferons, being able to both induce some STAT signaling and trigger cell death. Finally, it should be stressed that our data does not exclude the possibility that IFN-λ triggers cell death using ISGs that are accumulated (mostly) due to IFN-β signaling. This is in line with the observation that the effect of IFNLR1 deficiency is the strongest when cells are already prestimulated with IFN-β, and our earlier study (Czerkies *et al*, 2018) which showed that the death rate after poly(I:C) stimulation is much higher in IFN-β-prestimulated cells.

Methods

Cell lines and cultures. The A549, HEK-293T, HeLa and MDCK cell lines were purchased from the ATCC. A549 cells were cultured in F-12K basal medium supplemented with 10% fetal bovine serum (FBS) and a penicillin-streptomycin antibiotic solution. MDCK, HeLa cells and HEK-293T cells were maintained in Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% FBS and a penicillin-streptomycin antibiotic solution. All cell lines were cultured under standard conditions (37°C with 5% CO_2) and kept in monolayers up to 90% confluence. The IFNAR1, IFNLR1, and IFNAR1-IFNLR1 knockouts based on the A549

cell line were developed using the CRISPR lentivirus system (Abm). The detailed procedure for obtaining these cell lines have been described in (Czerkies *et al*, 2022, see Methods section and Supplementary Figure S3 therein).

Virus amplification and isolation. Respiratory syncytial virus strain A2 and influenza A virus H1N1 strain A/PR/8/34 were purchased from the ATCC and amplified in HeLa and MDCK cells, respectively. Cells were seeded into 225-cm^2 tissue culture flasks (Falcon) and cultured as described above for 2 to 3 days until they reached 90% confluence. On the day of infection, the following virus growth medium was prepared: DMEM with 2% FBS for RSV or basal minimal essential medium (MEM) with 0.3% bovine serum albumin (BSA) and 1 µg/mL of L-1-tosylamido-2-phenylethyl chloromethyl ketone (TPCK-trypsin) for IAV. The dilutions of the virus were prepared in an appropriate medium, with target MOIs of around 0.01 for RSV and 0.05 for IAV. Culture media were removed, and cells were washed once with phosphate-buffered saline (PBS) and overlaid with 10 mL of the inoculum. Virus was allowed to adsorb to cells for 2 h at 37°C, with occasional stirring. Next, additional virus growth medium was added to a total volume of 40 mL per flask. Infected cells were cultured at 37°C until the development of cytopathic effects could be observed in at least 80% of the cells (typically at around 3 days for IAV and 5 days for RSV). Virus-containing culture fluid was then collected and clarified by centrifugation at 3,000×g at 4°C for 20 min. Next, virus particles were precipitated by adding 50% (wt/vol) polyethylene glycol 6000 (PEG 6000) (Sigma-Aldrich) in NT buffer (150 mM NaCl, 50 mM Tris-HCl [pH 7.5]) to a final concentration of 10% and stirring the mixture gently at 4°C for 90 min. Virus was centrifuged at 3,250×g at 4°C for 20 min and recentrifuged after the removal of the supernatant to remove the remaining fluid. The pellet was suspended in 1 mL of NT buffer or in 20% sucrose in NT buffer in the case of RSV, aliquoted, and stored at −80°C.

Virus quantification. The virus concentration in the collected samples was quantified using an immunofluorescence protocol. HeLa or MDCK cells were seeded onto microscopic coverslips and cultured upon reaching 90 to 100% confluence. Serial dilutions of virus samples were made in virus growth medium in a range of 10−3 to 10−6. After washing with PBS, cells were overlaid in duplicates with diluted virus, which was allowed to adhere for 2 h, with occasional stirring. Afterward, the virus-containing medium was removed, and cells were overlaid with fresh virus growth medium and cultured for 16 h (for IAV) or 24 h (for RSV). Next, cells were washed with PBS and fixed with 4% formaldehyde for 20 min at room temperature. Cells were stained using a standard immunofluorescence protocol with anti-RSV antibody (catalog number ab43812; Abcam) or anti-influenza A virus nucleoprotein antibody (clone C43) (catalog number ab128193; Abcam). Cells containing stained viral proteins were counted using a Leica SP5 confocal microscope. The virus concentration was

calculated using the following formula: (average number of infected cells)/(dilution factor × volume containing virus added) = infectious particles/mL. For a given MOI, we observe fewer cells expressing viral proteins in the A549 than in the HeLa and MDCK lines, which are known to be permissive for RSV and IAV infections, respectively.

Compounds and stimulation protocols. Human IFN-β1A and IFN-λ1 were purchased from Thermo Fisher Scientific (catalog numbers PHC4244 and 34-8298-64, respectively) and prepared according to the manufacturer's instructions. For cell stimulation, interferons were further diluted to the desired concentrations in F-12K medium supplemented with 2% FBS. The decreased FBS content was used to prevent the inhibition of viral attachment and entry at the second stage of the experiments.

For interferon–virus experiments, the cell culture media were exchanged for interferon-containing or control media at time zero and were not removed afterward until the end of the experiment. Appropriately diluted virus was added in small volumes (less than 10 μL) directly into the wells. The even distribution of virus across the cell population was aided by the intermittent rocking of the plate for 2 h.

Antibodies. (i) Antibodies for Western blotting. Primary antibodies for Western blotting were anti-phospho-STAT1 (Tyr701) (clone 58D6) (catalog number 9167; Cell Signaling Technologies) (1:1,000), anti-phospho-STAT2 (Tyr690) (clone D3P2P) (catalog number 88410; Cell Signaling Technologies) (1:1,000), anti-RIG-I (clone D14G6) (catalog number 3743; Cell Signaling Technologies) (1:1,000), anti-STAT1 (catalog number 610116; BD Biosciences) (1:1,000), anti-STAT2 (catalog number PAF-ST2; R&D Systems) (1:1,000), anti-PKR (clone B-10) (catalog number sc-6282; Santa Cruz Biotechnology) (1:1,000), anti-OAS1 (clone F-3) (catalog number sc-374656; Santa Cruz Biotechnology) (1:1,000), anti-influenza A virus nucleoprotein (clone C43) (catalog number ab128193; Abcam) (1:1,000), anti-respiratory syncytial virus (clone 2F7) (catalog number ab43812; Abcam) (1:1,000), and hFAB rhodamine anti-glyceraldehyde-3-phosphate dehydrogenase (GAPDH) (catalog number 12004168; Bio-Rad) (1:10,000).

Secondary antibodies for Western blotting were DyLight 800 4× PEG-conjugated goat anti-rabbit IgG(H+L) (catalog number SA5-35571; Thermo Fisher Scientific) (1:10,000), DyLight 800 4× PEG-conjugated goat anti-mouse IgG(H+L) (catalog number SA5-35521; Thermo Fisher Scientific) (1:10,000), StarBright Blue 700-conjugated goat anti-mouse IgG (catalog number 12004159; Bio-Rad) (1:10,000), and horseradish peroxidase (HRP)-conjugated rabbit anti-goat immunoglobulins (catalog number P0449; Agilent) (1:10,000).

(ii) Antibodies for immunostaining. Primary antibodies for immunostaining were anti-phospho-STAT1 (Tyr701) (clone 58D6) (catalog number 9167; Cell Signaling Technologies) (1:1,000), anti-respiratory syncytial virus (catalog number ab20745; Abcam) (1:1,000), anti-influenza A virus (catalog number ab20841; Abcam) (1:1,000), anti-influenza A virus nucleoprotein (clone C43) (catalog number ab128193; Abcam) (1:1,000), and anti-human interferon beta (catalog number MAB8142; R&D Systems).

Secondary antibodies for immunostaining were Alexa Fluor 488-conjugated donkey anti-rabbit IgG(H+L) (catalog number A-21206; Thermo Fisher Scientific) (1:1,000), Alexa Fluor 555-conjugated donkey anti-mouse IgG(H+L) (catalog number A-31570; Thermo Fisher Scientific) (1:1,000), and Alexa Fluor 633-conjugated donkey anti-goat IgG(H+L) (catalog number A-21082; Thermo Fisher Scientific) (1:1,000).

RNA isolation. For gene expression analysis experiments, cells were seeded on 12- or 24-well plates (Falcon) at a density of, respectively, 1.0× or 1.5×10^5 cells/well. Upon completed stimulation according to chosen protocol, cells were washed once with PBS and submitted to isolation of total RNA using PureLink RNA Mini Kit (Thermo Fisher Scientific), following manufacturer's instructions: cells were harvested and vortexed in Lysis Buffer with 2-mercaptoethanol and then vortexed again with one volume of 70% ethanol. Upon transferring to the spin cartridge, cellular RNA content was bound to the column, washed with appropriate buffers and eluted, all by centrifugation at 12,000×*g*. Eluted RNA in RNase-free water was used immediately for reverse transcription or stored for later use at −80 °C.

Reverse transcription. RNA concentration and quality was determined by measuring UV absorbance of samples diluted 1:100 in 10 mM Tris-HCl (pH 7.5) at 260 and 280 nm, using the Multiskan GO spectrophotometer (Thermo Fisher Scientific). Independently, RIN index for isolated RNA was checked using Agilent 2100 Bioanalyzer (see below). Around 1 µg of RNA was used as a template for reverse transcription, performed using High-Capacity cDNA Reverse Transcription Kit (Thermo Fisher Scientific). Following manufacturer's protocol, diluted RNA samples were mixed 1:1 with freshly prepared Master Mix containing RT Buffer, RT Random Primers, dNTP Mix, MultiScribe Reverse Transcriptase and RNase Inhibitor. Reaction was performed in Mastercycle Gradient thermal cycler (Eppendorf) under following conditions: 10 min at 25 °C, 120 min at 37 °C, and 5 min at 85 °C.

Real-Time Quantitative Polymerase Chain Reaction. Reaction was performed on a QuantStudio 12K Flex Real-Time PCR system with Array Card block (Life Technologies). In most cases, 750 ng of cDNA from reverse transcription was mixed with reaction Master Mix and loaded onto TaqMan Array Card containing probes and primers for 24 genes (in 2

replicates), including endogenous reference controls (see Source Data S2). Reaction was conducted using QuantStudio “Standard” protocol, with FAM/ROX chemistry. Upon completion, expression of target genes was analyzed based on absolute Ct quantification or classical ΔΔCt method with QuantStudio 12K Flex software, normalized against GAPDH gene expression.

Digital PCR. For gene expression experiments, cells were seeded onto 24-well plates at a density of 100,000 cells per well. RNA from virus-infected cells was isolated using a PureLink RNA Mini kit (Thermo Fisher Scientific) according to the manufacturer’s instructions: cells were harvested and vortexed in lysis buffer with 2-mercaptoethanol and then vortexed again with 1 volume of 70% ethanol. Upon transfer to the spin cartridge, the cellular RNA content was bound to the column, washed with the appropriate buffers, and eluted, all by centrifugation at 12,000×*g*. The eluted RNA in RNase-free water was used immediately for reverse transcription (RT) or stored for later use at −80°C. The concentration and quality of the isolated total RNA were determined by measuring the UV absorbance at 260 nm and 280 nm using a Multiskan Go spectrophotometer (Thermo Fisher Scientific). Approximately 0.5 µg of RNA was used as a template for reverse transcription, performed using a high-capacity cDNA reverse transcription kit (Thermo Fisher Scientific): the diluted RNA samples were mixed 1:1 with freshly prepared master mix containing RT buffer, RT random primers, deoxynucleoside triphosphate (dNTP) mix, MultiScribe reverse transcriptase, and an RNase inhibitor. The reaction was performed in a Mastercycler gradient thermal cycler (Eppendorf) under the following conditions: 10 min at 25°C, 120 min at 37°C, and 5 min at 85°C.

Measurements of the viral RNA copy number were then performed using the QuantStudio 3D system (Thermo Fisher Scientific) and TaqMan Vi99990011_po and Vi99990014_po gene expression assays for the quantification of IAV and RSV RNAs, respectively. Appropriately diluted samples were mixed with the reaction master mix and the chosen assay mix, loaded onto the digital PCR (dPCR) chips in duplicates, and thermocycled using a ProFlex flat-block thermal cycler. Subsequently, chips were analyzed with a QuantStudio 3D digital PCR instrument. The chip quality check and final data analysis were performed using QuantStudio 3D AnalysisSuite software.

Western blotting. Cells at the indicated time points were washed twice with PBS, lysed in Laemmli sample buffer containing dithiothreitol (DTT), and boiled at 95°C for 10 min. Equal amounts of each protein sample were separated on 4 to 16% Mini-Protean TGX stain-free precast gels using the Mini-Protean Tetra cell electrophoresis system (Bio-Rad). Upon the completion of electrophoresis, proteins were transferred to a nitrocellulose membrane using

wet electrotransfer in the Mini-Protean apparatus (400 mA for 50 min). The membrane was rinsed with TBST (Tris-buffered saline [TBS] containing 0.1% Tween 20; Sigma-Aldrich) and blocked for 1 h with 5% BSA–TBS or 5% nonfat dry milk. Subsequently, the membranes were incubated with one of the primary antibodies diluted in a 5% BSA–TBS buffer at 4°C overnight. After thorough washing with TBST, the membranes were incubated with secondary antibodies conjugated to a specific fluorochrome (DyLight 800; Thermo Fisher Scientific) or horseradish peroxidase (HRP-conjugated polyclonal anti-mouse/anti-rabbit immunoglobulins; Dako) diluted 1:5,000 in 5% nonfat dry milk–TBST for 1 h at room temperature. The chemiluminescence reaction was developed with the Clarity Western ECL system (Bio-Rad). For GAPDH detection, hFAB rhodamine anti-GAPDH primary antibody (Bio-Rad) was used. Specific protein bands were detected using the ChemiDoc MP imaging system (Bio-Rad).

Immunostaining. For staining of intracellular proteins, cells were seeded onto 12-mm round glass coverslips, which were previously washed in 60% ethanol–40% HCl, thoroughly rinsed with water, and sterilized. After stimulation with interferon or viral infection at the desired time points, cells on the coverslips were washed with PBS and immediately fixed with 4% formaldehyde (20 min at room temperature). Cells were then washed three times with PBS and incubated with 100% cold methanol for 20 min at −20°C. After washing with PBS, coverslips with cells were blocked and permeabilized for 1.5 h with 5% BSA (Sigma-Aldrich) with 0.3% Triton X-100 (Sigma-Aldrich) in PBS at room temperature. After the removal of the blocking solution, coverslips with cells were incubated with primary antibodies diluted in PBS containing 1% BSA and 0.3% Triton X-100 overnight at 4°C. After the cells were washed five times with PBS, the appropriate secondary antibodies conjugated with fluorescent dyes were added, and the cells were incubated for 1 h at room temperature. Subsequently, the cells were washed, and their nuclei were stained with 200 ng/mL 4′,6-diamidino-2-phenylindole (DAPI) (Sigma-Aldrich) for 10 min. After a final wash in MilliQ water, coverslips with stained cells were mounted onto microscope slides with a drop of Mowiol (Sigma-Aldrich).

FACS/cell death assay. Cell death was measured using annexin V and propidium iodide staining method (FITC Annexin V Apoptosis Detection Kit II, BD Bioscience), measuring the amount of phosphatidylserine externalized to the outer layer of cell membrane. For the analysis, cells were seeded on 12-well plates at a density of 100,000 cells/well and treated according to the chosen protocol. Analysis was performed on both the cells attached to the plate surface and dying cells suspended in the medium. Flow cytometry measurement was performed using FACSCalibur (BD) and the CellQuest Pro analysis software. Cells which are both annexin V- and propidium iodide (PI)-negative were considered viable, annexin V-

positive and PI-negative were considered early apoptotic or pyroptotic; PI-positive cells, irrespective of the outcome of annexin V staining, were considered dying or dead.

Live imaging propidium iodide assay. To estimate cell death rates during infection with IAV and RSV, live imaging of PI intracellular accumulation was performed. One day before the experiment, cell nuclei were stained with Hoechst 33342 (Thermo) diluted 1 µg/ml in PBS for 10 minutes at 37°C. After staining, the cells were washed and seeded onto a µClear 96-well microplate at a density of 18,000 cells per well. The following day, the cells were infected with IAV or RSV, and PI was added. Cells were observed for 24 or 48 h, and within these periods fraction of PI positive cells was determined. After 24 or 48 h p.i. cell fixation and immunostaining were performed to estimate the number of infected cells. Imaging was carried out on an Operetta CLS (PerkinElmer) using Harmony software. Images were analyzed using our in-house software, ShuttleTracker (see the Data analysis section).

Image analysis. Confocal images obtained from immunostaining were analyzed using our in-house software (https://pmbm.ippt.pan.pl/software/shuttletracker). Nuclear outlines were detected based on DAPI staining. Outlines of nuclei that were partially out of frame or mitotic were excluded from the analysis; outlines of overlapping nuclei were split based on geometric convexity defects when possible. Cells were classified as either virus-negative or virus-positive based on the sum of the intensities of the pixels inside nuclear outlinesCells were classified as dead/dying based on the intensities of pixels inside nuclear outlines in the PI channel.

Statistical analysis. To assess statistical significance we performed the following tests: Student *t*-test (Fig. 1B, Figs. 2B and 2D, Figs. 3B and 3D, Figs. 4A and 4B, Fig. 6B, Fig. EV4), Wilcoxon signed-rank test (Fig. 1C, Fig. 6B), unpaired Student *t*-test (Fig. 6A), Mann-Whitney *U* test (Fig. 6A). All tests assume two-tailed alternatives.

In most cases (Figs. 1B and 1C, Figs. 2B and 2D, Fig. 4A, Fig. 6A and 6B, Fig. EV4), the statistical tests were performed using experimental replicates obtained for two or three time points pooled together; similarly, in Fig. 4A and Fig. EV4 two MOI values (0.01 and 0.1) are considered jointly. This approach is demonstrated in five cases below, with the remaining cases treated analogously.

In Fig. 1C we compared mRNA expression of ISGs after IFN-β and IFN-λ1 stimulation. To demonstrate that in the period between 6–24 hours, mRNA expression is significantly higher after IFN-β stimulation than after IFN-λ1 stimulation, we performed 3 experimental replicates in which mRNA levels were measured at 3 time points: 6, 10 and 24 h post stimulation; data at each time point was gathered from a separate dish. We then compare these 9 pairs (IFN-

β versus IFN-λ1) of data points using a single two-tailed Wilcoxon signed-rank test on paired differences. Pooling 3 different time points together is justified by the fact that the studied effect holds for all of them: for all but two ISGs we observed that in all replicates and at all time points mRNA expression after prestimulation with IFN-β is higher than after prestimulation with IFN-λ1.

In Fig. 1B, we perform a similar comparison by pooling measurements at 2 h with those at 6 h, and 24 h with 48 h in order to compare STAT1/2 and p-STAT1/2 levels after IFN-β and IFN-λ1 stimulation at an early time point (1 hour), for intermediate times (2–6 hours), and late times (24–48 hours). We performed a parametric two-tailed Student *t*-test on log ratios. In all cases where we report statistical significance, protein levels after IFN-β stimulation are consistently higher than after IFN-λ1 stimulation (for all replicates and pooled time points).

In Fig. 4A, we pooled together infection experiments with an MOI of 0.1 and 0.01 lasting 24 and 48 h. Again, by performing parametric two-tailed Student *t*-test on log ratios we showed that probing two MOI values and two infection times fraction of cells infected with IAV is higher for IFNLR1 KO than for WT cells.

In Fig. 6A, the left column consists of IAV NP level ratios between IFNLR1 KO and WT cells, where both levels are measured in a single Western blot. The right column consists of ratios between the fraction of dying/dead cells between IFNLR1 KO and WT cells; both fractions are measured in a single FACS experiment. However, ratios from the left column are not paired with ratios from the right column (since the Western blot and FACS measurements were not paired). Thus, we use a (parametric) unpaired Student *t*-test (without assuming equal variances) and a (non-parametric) Mann-Whitney *U* test to compare log ratios from the left column with log ratios from the right column. Data from time points 24 h p.i. and 48 h p.i. are considered jointly.

In Fig. 6B, ratios from the left column (obtained from immunostaining images of fixed cells) and ratios from the right column (obtained from live-cell imaging) are paired, since both types of measurement were performed for the same cell population (for each experimental replicate). For each left–right pair, we can thus compute a ratio-of-ratios. We then perform a (parametric) two-tailed Student *t*-test and a (non-parametric) two-tailed Wilcoxon signed-rank test on log ratio-of-ratios. Data from time points 24 h p.i. and 48 h p.i. and cell lines WT and IFNLR1 KO are considered jointly, since the death rate in IAV is always higher than in RSV (which is equivalent to ratio-of-ratios greater than 1).

Data availability

All Western blots performed for this study are available in supplementary file Source Data S1. Quantifications of Western blots, RT-PCR, digital PCR, FACS, imaging data and codes to generate figures are available in supplementary file Source Data S2. The raw imaging dataset is available at Zenodo (doi: 10.5281/zenodo.13735878).

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Data curation: Frederic Grabowski, Marek Kochańczyk.

Writing – original draft: Frederic Grabowski, Marek Kochańczyk, Tomasz Lipniacki.

Writing – review & editing: Wiktor Prus, Frederic Grabowski, Paulina Koza, Zbigniew Korwek, Maciej Czerkies, Marek Kochańczyk, Tomasz Lipniacki.

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Funding acquisition: Tomasz Lipniacki.

Disclosure and competing interest statement

The authors declare no competing interests.

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Figures

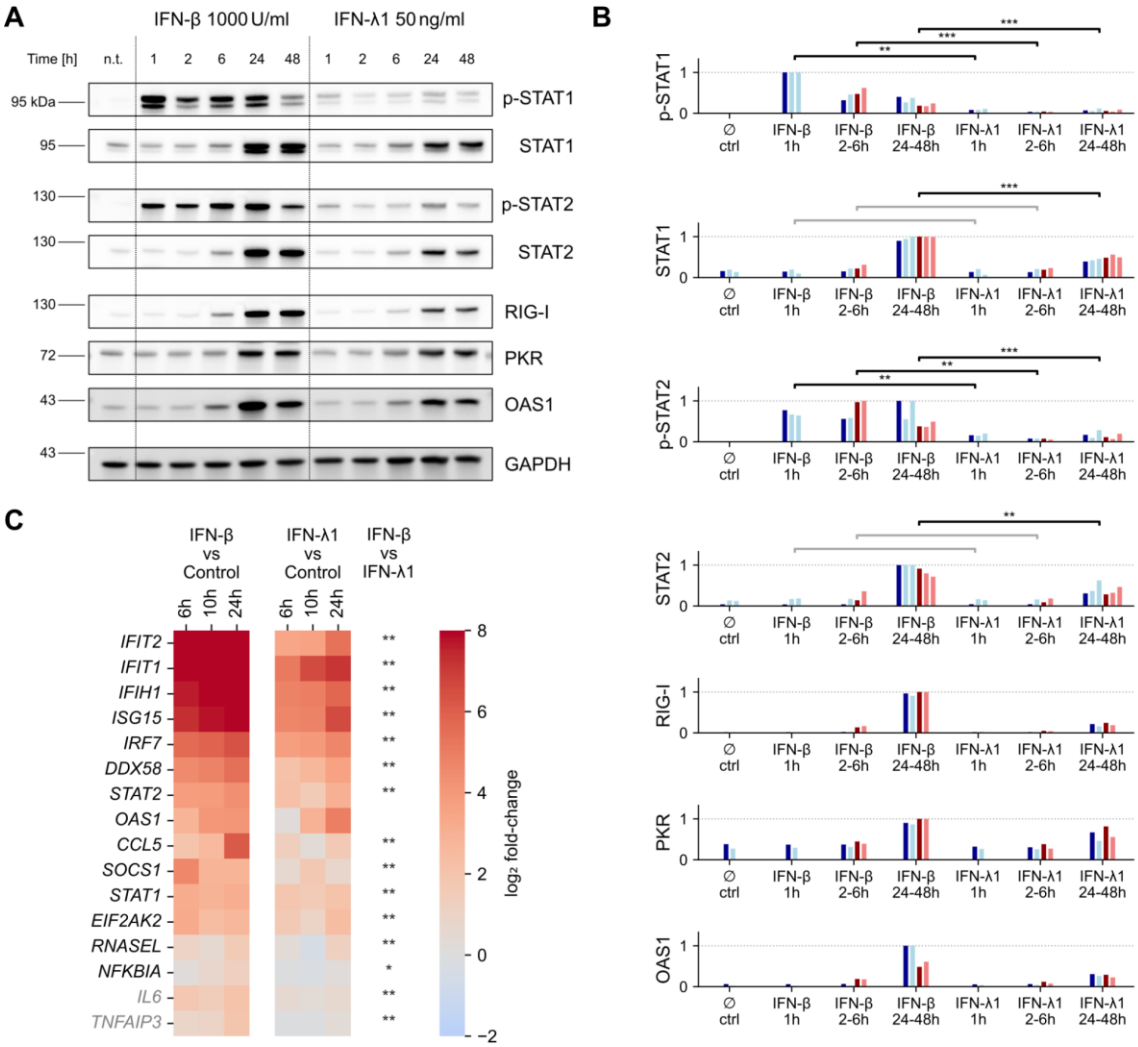
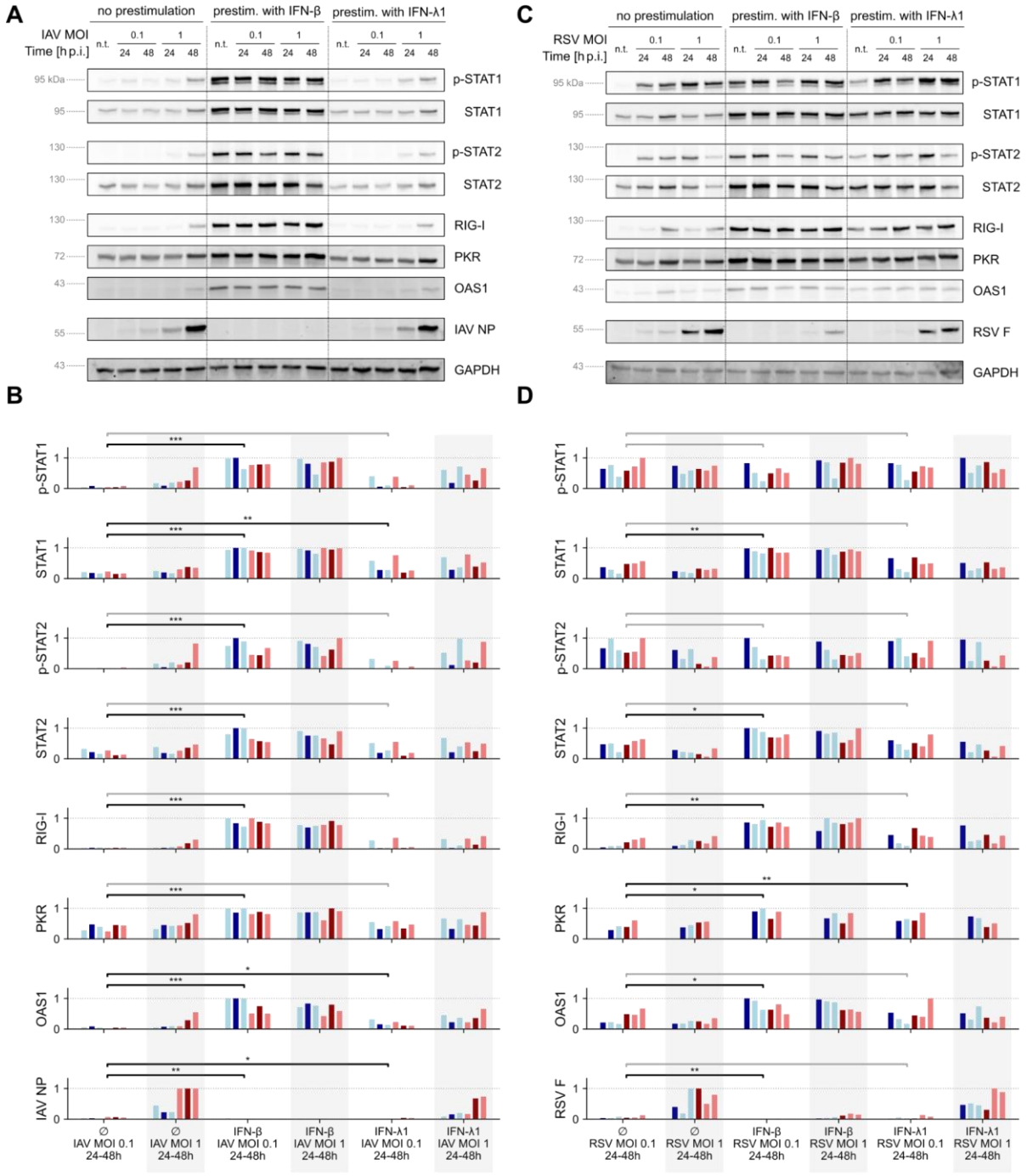


Figure 1. STAT1/2 activation and accumulation of ISGs after stimulation with IFN-β and IFN-λ1.

A A549 cells were stimulated with IFN-β (1000 U/ml) or IFN-λ1 (50 ng/ml) for 1, 2, 6, 24, or 48 h before lysis; p-STAT1, STAT1 phosphorylated at Tyr701; p-STAT2, STAT2 phosphorylated at Tyr690.

B Quantification of two or three experimental replicates (as shown). Blue bars indicate control and time points of 1, 2, and 24 h; red bars indicate 6 and 48 h; darker color indicates the experimental replicate shown in panel A. Each blot quantification is normalized to the maximum. The significances $p < 0.001$ (***) and $p < 0.01$ (**) were determined using a two-tailed Student *t*-test on log ratios.

C RT-PCR of common ISGs as well as *IL6* and *TNFAIP3* after 6, 10, and 24 h stimulation with either IFN-β (1000 U/ml) or IFN-λ1 (50 ng/ml). The averaged $\log_2$ difference (based on 3 experimental replicates) with respect to control is shown. Asterisks indicate that expression of a given gene after stimulation with IFN-β is significantly higher than after IFN-λ1 at $p < 0.05$ (*) or $p < 0.01$ (**); two-tailed Wilcoxon signed-rank test on paired differences; three time points are considered jointly.


A
no prestimulation
prestim. with IFN-β
prestim. with IFN-λ1
IAV MOI
Time [h p.i.]
n.t.
0.1
1
24
48
95 kDa
p-STAT1
STAT1
p-STAT2
STAT2
RIG-I
PKR
OAS1
IAV NP
GAPDH
C
RSV MOI
RSV F
B
D
∅
IFN-β
IFN-λ1
IAV MOI 0.1
IAV MOI 1
RSV MOI 0.1
RSV MOI 1
24-48h

654

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Figure 2. Effect of the prestimulation with IFN-β and IFN-λ1 on STAT1/2 activation, expression of ISGs, and virus proliferation.

A A549 cells were prestimulated with either IFN-β or IFN-λ1 (or mock) 24 h before infection with IAV at MOI of 0.1 or 1 and lysed 24 or 48 h post infection (p.i.). Label 'n.t.' denotes cells not treated with a virus.

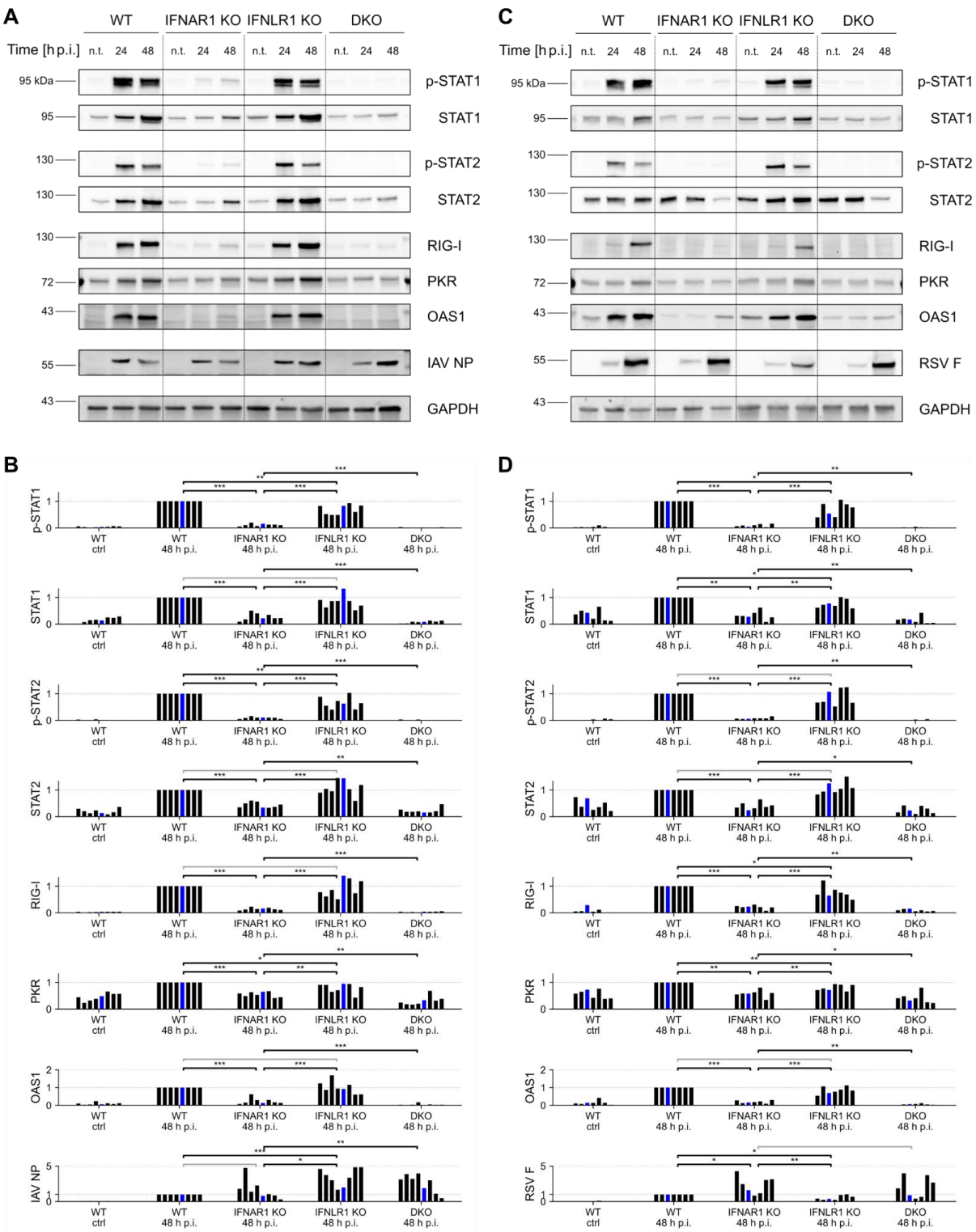
B Quantification of three replicates of the experiment shown in A. Values for 24 h p.i. and 48 h p.i. are shown in blue and red, respectively. Darker hues correspond to the blot shown in panel A are shown in blue.

C A549 cells were prestimulated with IFN-β or IFN-λ1 (or mock) 24 h before infection with RSV at an MOI of 0.1 or 1 and lysed 24 or 48 h after the infection. Label 'n.t.' denotes cells not treated with a virus.

D Quantification of three replicates of the experiment shown in C. Values for 24 h p.i. and 48 h p.i. are shown in blue and red, respectively. Darker hues correspond to the blot shown in panel A are shown in blue.

In panels A and C, due to all available 15 lanes being used for probes, the marker lane was omitted. Locations of molecular weight markers were determined based on previous experiments.

In panels B and D, quantification of the bands without infection with IAV or RSV (n.t.) are omitted. Each blot quantification is normalized to the maximum. The significances $p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*) were determined using a two-tailed Student *t*-test on log ratios.


A
WT
IFNAR1 KO
IFNLR1 KO
DKO
Time [h p.i.]
n.t.
24
48
95 kDa
p-STAT1
STAT1
p-STAT2
STAT2
RIG-I
PKR
OAS1
IAV NP
GAPDH
C
RSV F
B
D
WT ctrl
WT 48 h p.i.
IFNAR1 KO 48 h p.i.
IFNLR1 KO 48 h p.i.
DKO 48 h p.i.

677

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Figure 3. Effect of IFNLR1 and IFNAR1 knockout on IAV and RSV proliferation and activation of immune response

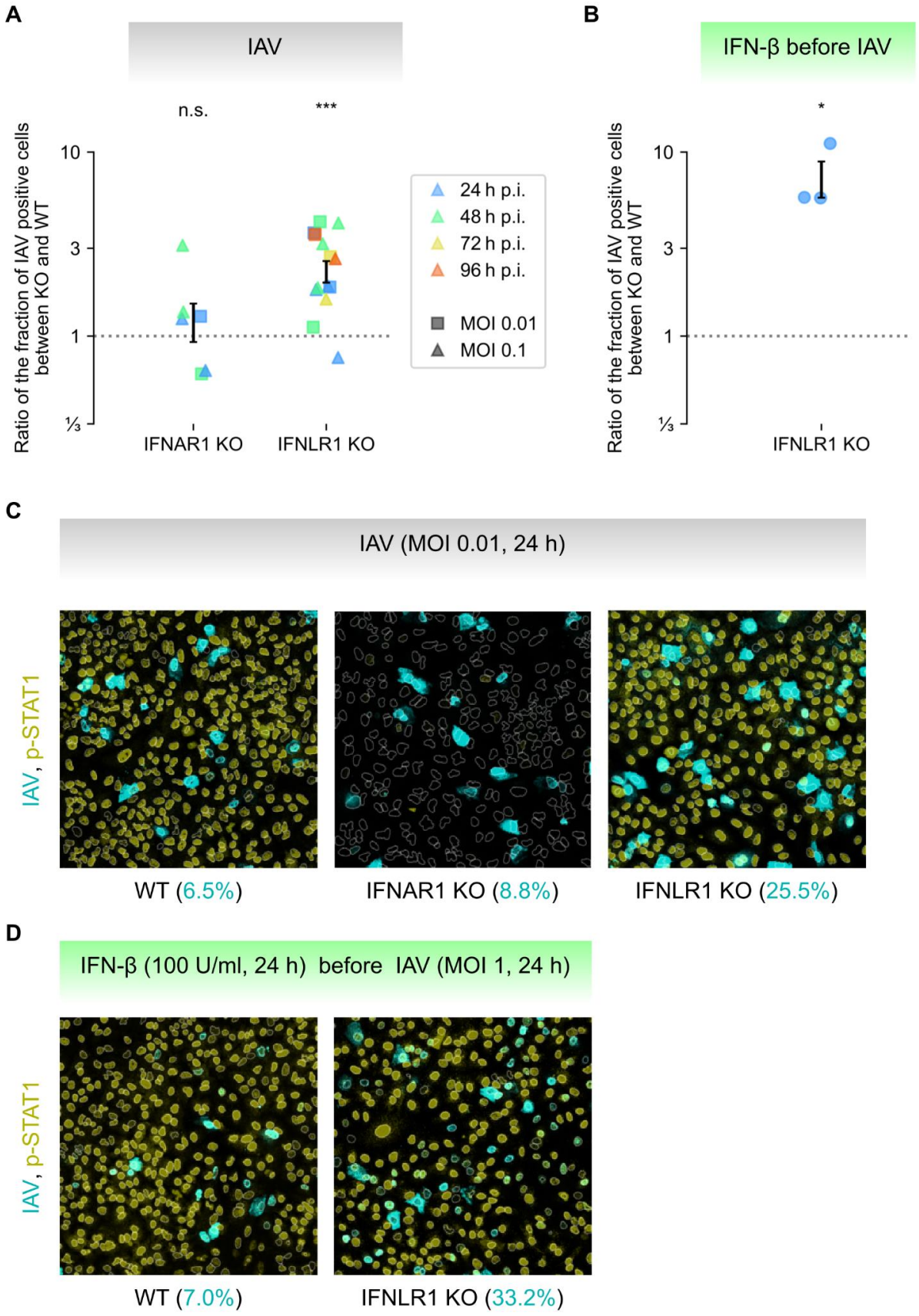
A A549 WT, IFNAR1 KO, IFNLR1 KO, and IFNAR1 & IFNLR1 double KO (DKO) cells were infected with IAV at an MOI of 0.1 and lysed 24 or 48 h p.i.

B Quantification of selected bands from blots in panel A and its seven replicates at 48 h Quantification of the shown blot is marked in blue.

C A549 WT, IFNAR1 KO, IFNLR1 KO and DKO cells were infected with RSV at an MOI of 0.1 and lysed 24 or 48 h p.i.

D Quantification of selected bands from blots in panel C and its six replicates at 48 h. Quantification of the shown blot is marked in blue.

In panels B and D, $p < 0.001$ (***), $p < 0.01$ (**), and $p < 0.05$ (*) were determined using a two-tailed Student *t*-test on log ratios. Only selected pairwise differences between WT, IFNAR1 KO, IFNLR1 KO, and DKO cells were considered. Each blot quantification is normalized to the value from WT cells at 48 h p.i. The quantification of all time points from blots in A and C is shown in Figs. EV2 and EV3.


A
IAV
n.s.
***
Ratio of the fraction of IAV positive cells between KO and WT
10
3
1
⅓
IFNAR1 KO
IFNLR1 KO
24 h p.i.
48 h p.i.
72 h p.i.
96 h p.i.
MOI 0.01
MOI 0.1
B
IFN-β before IAV
*
Ratio of the fraction of IAV positive cells between KO and WT
10
3
1
⅓
IFNLR1 KO
C
IAV (MOI 0.01, 24 h)
IAV, p-STAT1
WT (6.5%)
IFNAR1 KO (8.8%)
IFNLR1 KO (25.5%)
D
IFN-β (100 U/ml, 24 h) before IAV (MOI 1, 24 h)
IAV, p-STAT1
WT (7.0%)
IFNLR1 KO (33.2%)

694

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Figure 4. Effect of IFNLR and IFNAR knockout on IAV propagation and activation of immune response

A Fraction of IAV-positive cells in A549 IFNAR1 KO and IFNLR1 KO with respect to the fraction observed for WT. Quantification of three experimental replicates, $p < 0.001$ (***) according to the two-tailed Student *t*-test on log ratios for 24 and 48 h p.i. and MOIs of 0.01 and 0.1 considered jointly.

B Fraction of IAV positive cells in A549 IFNAR1 KO with respect to the fraction observed for WT. Cells were prestimulated with IFN-β at a concentration of 100 U/ml 24 h before infection with IAV at an MOI of 1. Cells were fixed 24 h p.i. Quantification of three experimental replicates, $p < 0.05$ (*), paired two-tailed Student *t*-test on log ratios.

C Representative fields of view (FOV) showing immunostaining for IAV and p-STAT1 in A549 WT, IFNAR1 KO and IFNLR1 KO cells fixed 24 h p.i. with IAV at an MOI of 0.01. Percentages of infected cells in shown FOVs are given in cyan. All immunostaining images are available at Zenodo (see Data availability).

D Representative fields of view (FOV) showing immunostaining for IAV and p-STAT1 in A549 WT and IFNAR1 KO cells prestimulated with IFN-β at a concentration of 100 U/ml 24 h before infection with IAV at an MOI of 1, and fixed 24 h p.i. Percentages of infected cells in shown FOVs are given in cyan. All immunostaining images are available at Zenodo (see Data availability).

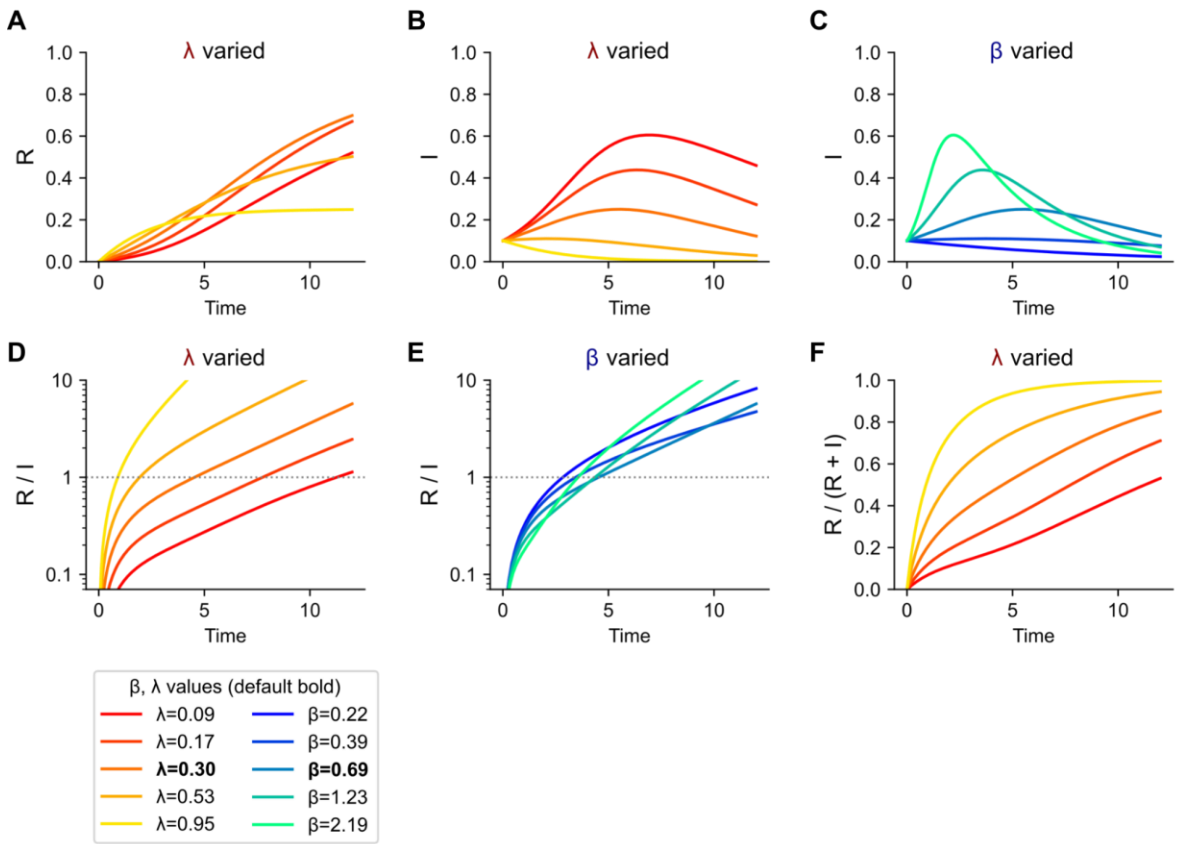

Figure 5. SIR model simulation. Influence of death and infection rates on virus propagation and cell death.

A, **B** Fraction of dead (**A**) or infected (**B**) cells as a function of time and the death rate λ.

C Fraction of infected cells (*I*) as a function of time and the infection rate β.

D, **E** Ratio of dead (*R*) to infected (*I*) fractions as a function of time and the death rate λ (**D**) or the infection rate β (**E**).

F Ratio of dead (*R*) to joint dead and infected (*R* + *I*) fractions as a function of time and the death rate λ.

In all panels, *I*(0) = 0.1, corresponding to MOI = 0.1. Unless specified otherwise, β = 0.69 and λ = 0.3. The default value of β was selected so that the initial doubling time is 1.

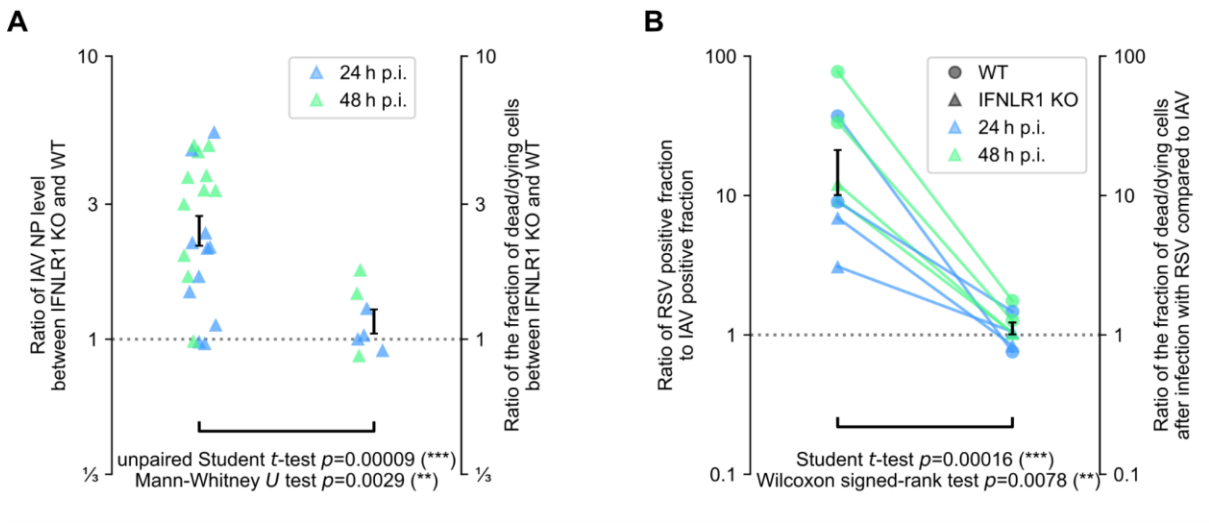

Figure 6. Influence of IFNLR1 deficiency and virus type on infected and dead cell fractions.

A Left: ratio of the IAV NP level between IFNLR1 KO and WT cells – calculated based on Western blots, using cells lysed 24 and 48 h p.i. at an MOI of 0.1. Right: ratio of the fraction of dying/dead cells 24 and 48 h p.i. between IFNLR1 KO and WT – calculated based on cell death assay using annexin V and propidium iodide staining (see Methods). Statistical significance was determined by performing an unpaired two-tailed Student *t*-test and a Mann-Whitney *U* test on log ratios (left *versus* right).

B Left: ratio of RSV-positive to IAV-positive cell fraction at 24 or 48 h p.i. at an MOI of 0.1 – calculated based on immunostaining images (with staining against respectively RSV and IAV). Right: ratio of the fraction of dead/dying cells after infection with RSV to an analogical fraction after infection with IAV. The dead/dying cells were counted based on the propidium iodide signal during live microscopy experiments lasting 24 or 48 h p.i. The same cells were fixed and immunostained to determine the fraction of virus-infected cells used in the left part of the panel. Statistical significance was determined by performing a two-tailed Student *t*-test and a two-tailed Wilcoxon signed-rank test on log ratio-of-ratios (left / right, see Methods).

Expanded View Figures

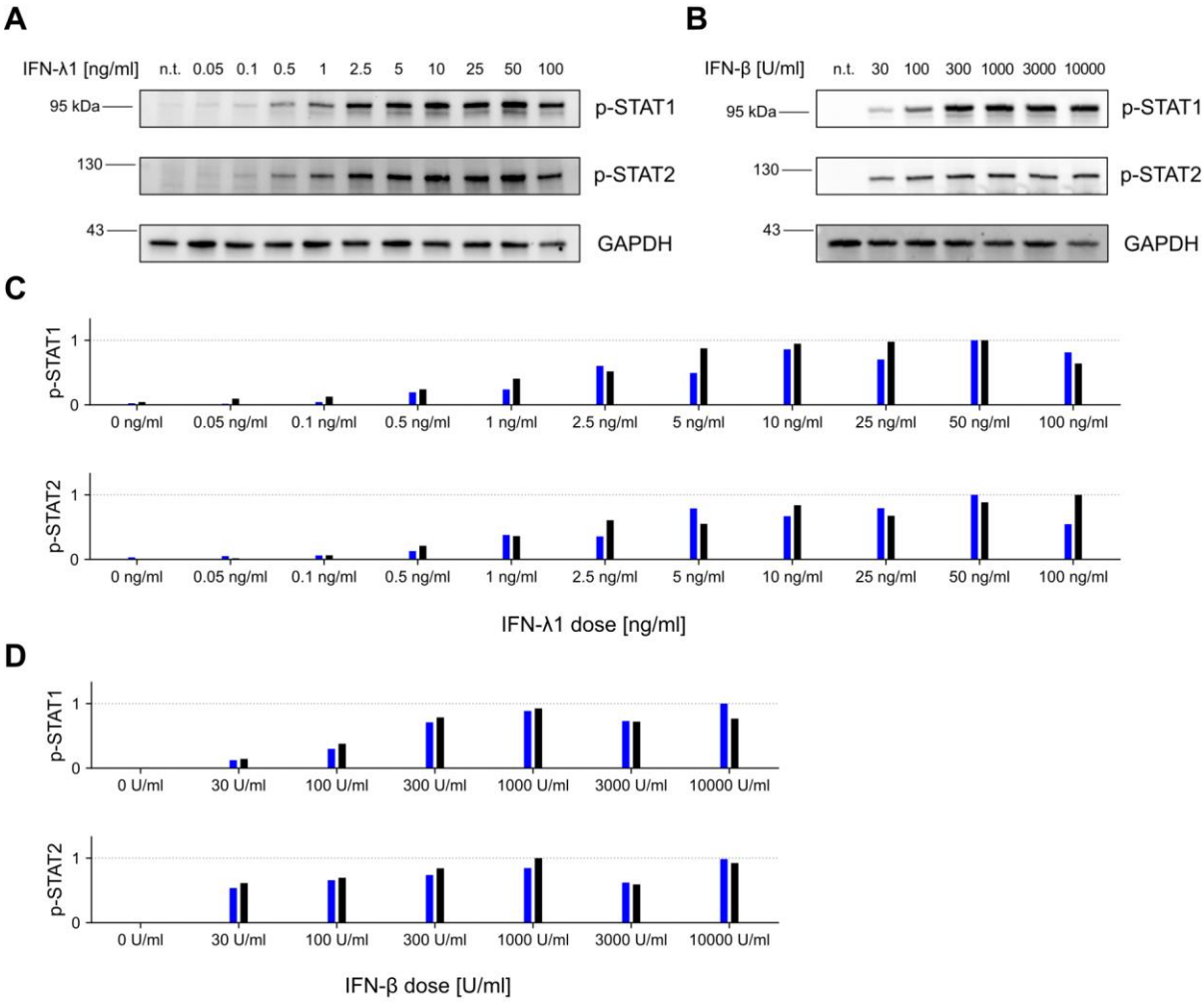

Figure EV1. IFN-β and IFN-λ dose–response analysis, determination of saturating concentrations.

A Cells were stimulated with an array of concentrations of IFN-λ1 for 30 min before lysis.

B Cells were stimulated with an array of concentrations of IFN-β for 30 min before lysis.

C Quantification of 2 experimental replicates, blot shown in panel A is marked in blue.

D Quantification of 2 experimental replicates, blot shown in panel B is marked in blue.

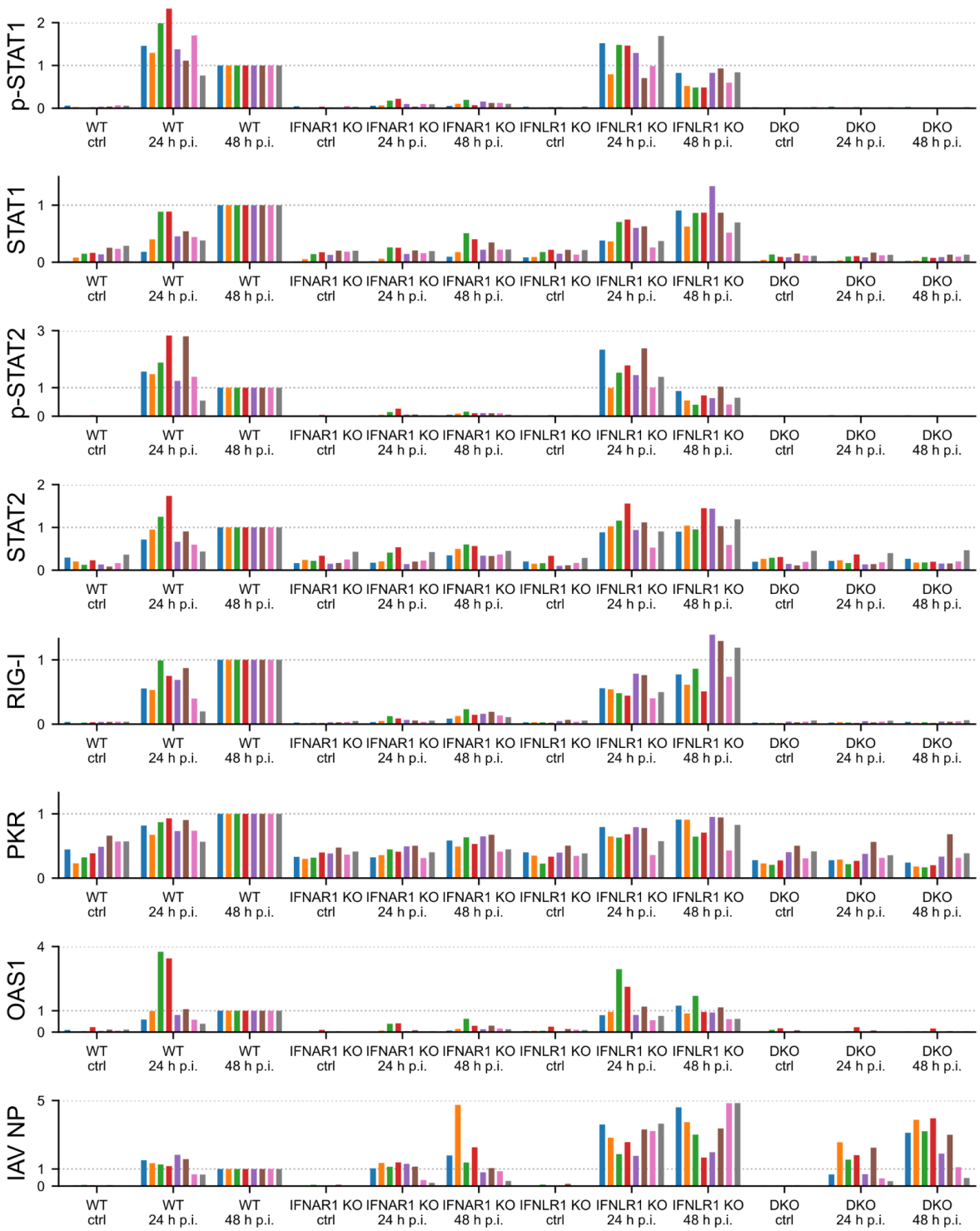

Figure EV2. Effect of IFNLR1 and IFNAR1 knockout on IAV proliferation and activation of the innate immune response – full quantification of experiments shown in Fig. 3A.

Colors correspond to independent experimental replicates of experiments shown in Fig. 3A.

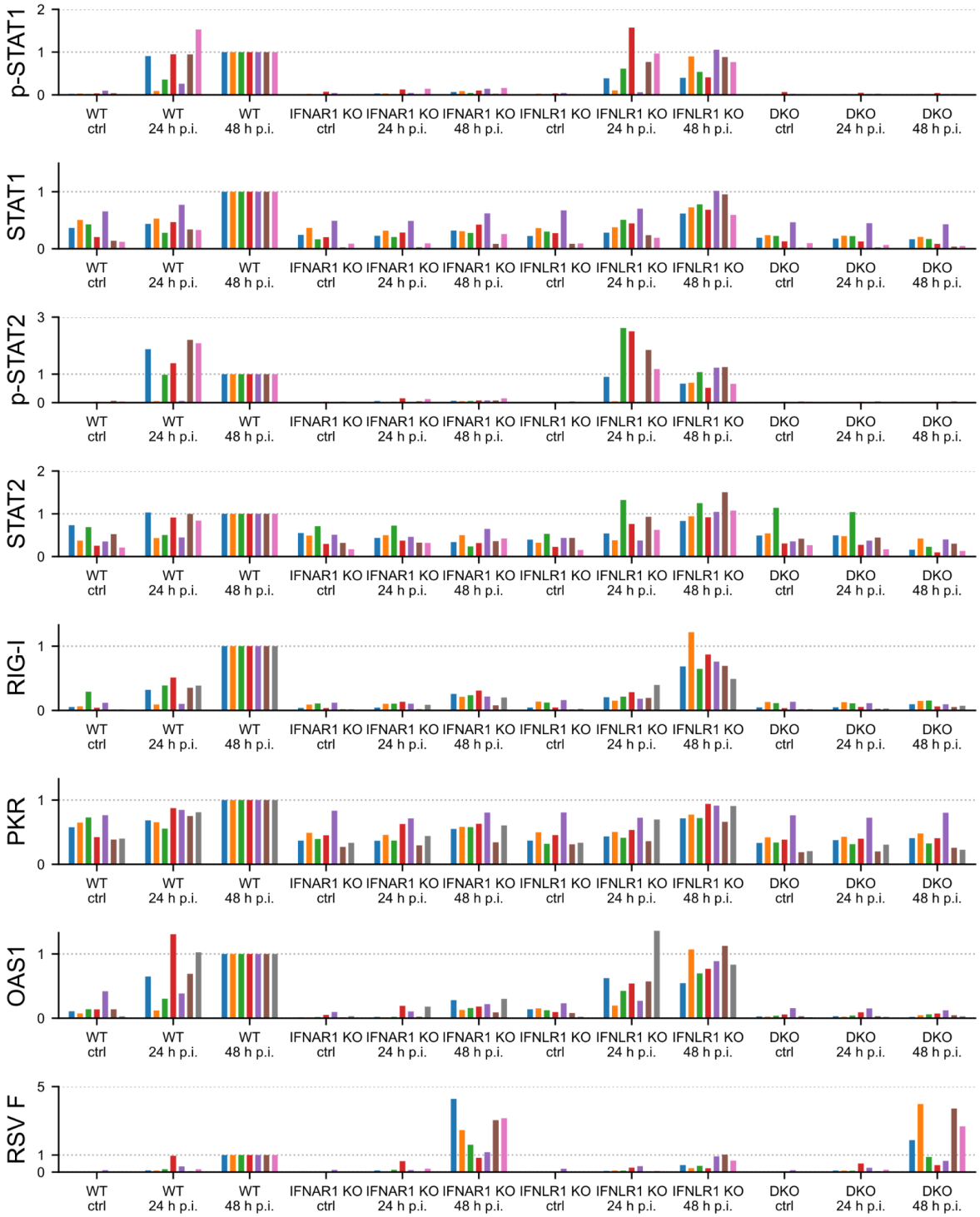

Figure EV3. Effect of IFNLR1 and IFNAR1 knockout on RSV proliferation and activation of the innate immune response – full quantification of experiments shown in Fig. 3B.

Colors correspond to independent experimental replicates of experiments shown in Fig. 3B.

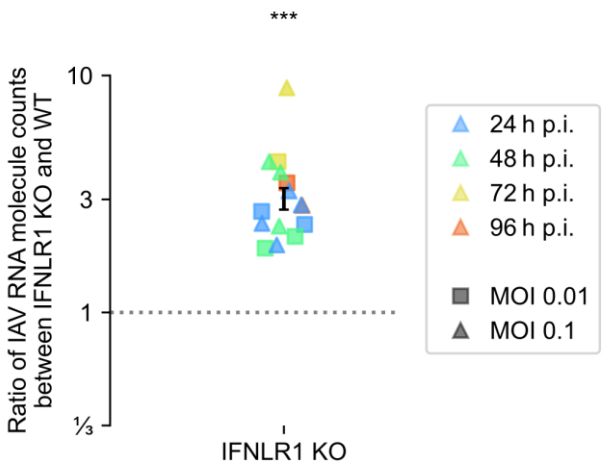

Figure EV4. Effect of IFNLR1 deficiency on IAV RNA expression.

Levels of IAV RNA were measured by dPCR for A549 WT and IFNLR1 KO cells at 24, 48, 72 and 96 h p.i. at MOIs of 0.01 and 0.1 (as indicated by the legend). Each square/triangle corresponds to an experimental replicate. Triple asterisk (***) indicates that IAV RNA expression is significantly higher in IFNLR1 KO cells than in WT cells ($p < 0.001$, paired two-tailed Student *t*-test on log ratios)

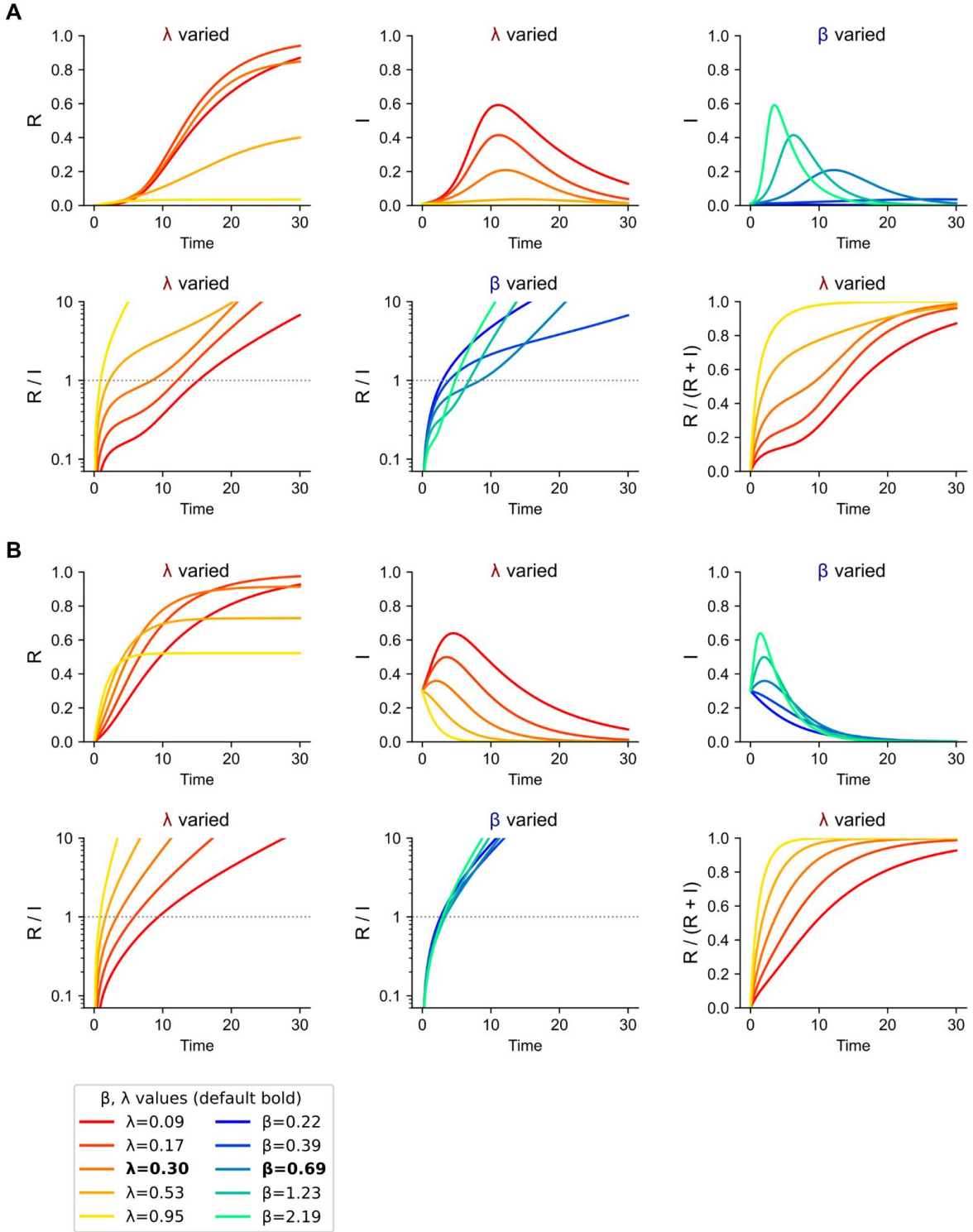

Figure EV5. Kinetics of infections in the SIR model. The figure supplements Fig. 5 with data for an MOI of 0.01 (A) and 0.3 (B).

Supplementary Data

Source Data S1 (PDF File). Images of all Western blot replicates.

Source Data S2 (Zipped folder). Data quantifications in CSV format (Western blots, dPCR, RT-PCR, FACS, cell counts from immunostaining) and Python codes to generate figures.